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MONTE CARLO CALCULATIONS OF A HEMISPHERICAL-DUCT NEUTRON-STREAMING EXPERIMENT

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16. Abstract

Two hemispherical-shell-duct neutron-streaming experiments were set up in a water tank. Each duct consisted of the air space between two concentric plexiglas hemispheres of different radii surrounded by water. The ducts were 12.2 and 7.0 cm wide with duct centerline radii of 35.0 and 45.1 cm, respectively. PuBe neutron sources were located in each duct. A 5.10- by 4.65-cm-diameter NE-213 scintillator was used to measure the neutron fluxes at the duct mouth for the ducts empty and flooded with water. Monte Carlo calculations of the fluxes were compared with measurements. Agreement was good for the ducts empty and fair for the ducts flooded.

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SUMMARY

Two hemispherical-shell-duct neutron-streaming experiments were set up in a water tank. Each duct consisted of the air space between two concentric plexiglas hemispheres of different radii. The ducts were 12.2 and 7.0 centimeters wide with spherical radii to the center of the ducts of 35.0 and 45.1 centimeters, respectively. Plutonium-beryllium (PuBe) neutron sources of 5 and 10 curies, respectively, were positioned at the bottom of the duct. A 5.10- by 4.65-centimeter NE-213 liquid organic scintillator was used to measure the intensity and spectra of neutrons leaking from the duct mouth with the duct both empty and flooded with water. The Oak Ridge National Laboratory (ORNL) unfolding technique was used to obtain the neutron spectra.

The experimental geometry was set up on the COHORT-II Monte Carlo shielding code, and the neutron intensity and spectra streaming from the ducts were calculated at point detectors.

The agreement between the calculated and measured spectra ranged from good to excellent for the empty ducts and was fair for the same detectors when the ducts were flooded. Estimated uncertainties in the calculated spectra were about 10 percent for the empty ducts and ranged from 10 to 50 percent for the flooded ducts. Statistical samples of 20 000 histories per detector were sufficient for the empty-duct calculations, but were inadequate for the flooded ducts although various biasing techniques were employed. Typical running time on the IBM 7094 was 25 minutes per detector for 20 000 histories.

INTRODUCTION

The design of a nuclear reactor shield is complicated by ducts, voids, and structural members which must pierce the shield. The analysis of such a shield is made difficult by radiation streaming through the ducts.

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One technique theoretically well suited for calculating the transmission of radiation through a duct-shield system is the Monte Carlo method. All the pertinent physical processes and complex three-dimensional geometries can be incorporated in the Monte Carlo calculation. However, the computation time required to achieve acceptable statistical precision increases with increasing geometric complexity and depth of penetration.

This report investigates the applicability of Monte Carlo calculations to neutron-streaming problems. Neutron-streaming experiments were conducted to test the capability of the Monte Carlo method. Two hemispherical shell ducts were set up in a water tank. Each duct consisted of the space between two concentric plexiglas hemispheres of different radii, with one duct having a smaller space between hemispheres and a larger spherical radius than the other. Plutonium-beryllium (PuBe) neutron sources were positioned at the bottom of each duct. Neutron intensity and spectra leaking out of the duct mouth were measured using an NE-213 scintillation detector. The duct radii were chosen so that no direct line-of-sight from source to detector was possible. The larger-radius duct was considered to be a more severe test of the Monte Carlo method because of the smaller duct width and the longer source-to-detector distance.

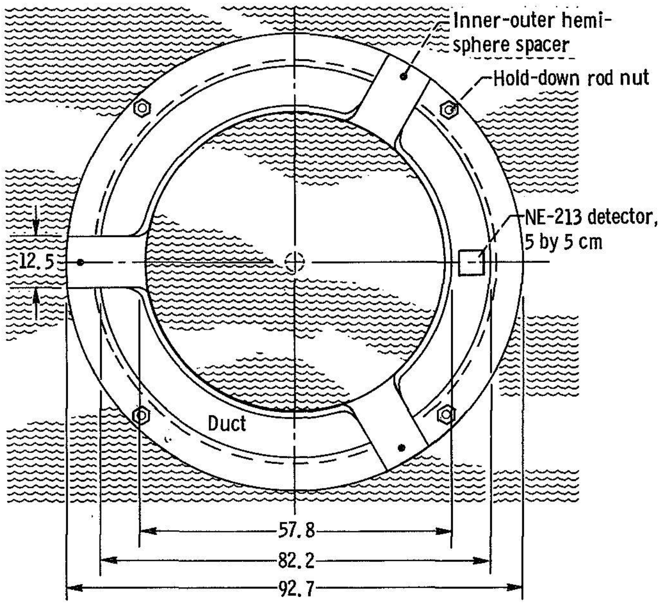
The COHORT-II Monte Carlo shielding code (ref. 1) was used to calculate these configurations. COHORT-II is a completely revised version of the original COHORT code (ref. 2) and has increased biasing capability and more flexible geometry.

EXPERIMENT

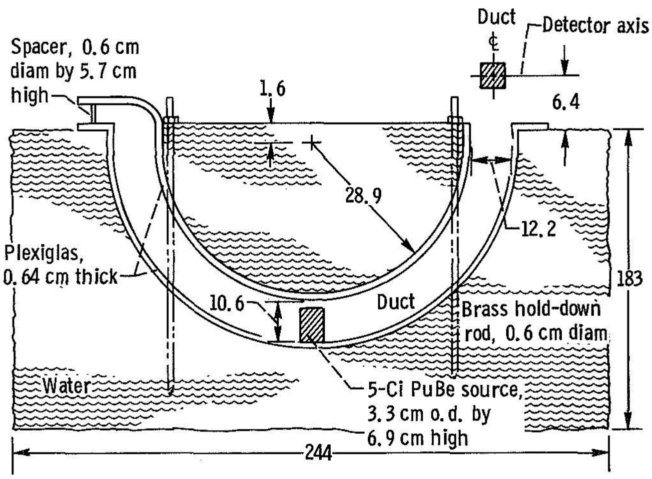
Duct Description

The duct shown in figure 1 was set up in a 244-centimeter-diameter by 183-centimeter-deep cylindrical tank of water using two plexiglas hemispheres. The 12.2-centimeter-wide duct was formed with two 0.64-centimeter-thick hemispheres by suspending a hemisphere with 57.8-centimeter outside diameter inside a hemisphere having an inside diameter of 82.2 centimeters. The center of the inner hemisphere was 1.6 centimeters lower than the center of the outer hemisphere when filled with water to a level equal with that of the tank, forming a duct width of 12.2 centimeters at the duct mouth and 10.6 centimeters at the duct bottom. The outer hemisphere, held down by four 0.6-centimeter-diameter brass rods, was immersed in water to its rim. The rods, bolted about the rim of the outer hemisphere, were fastened to the bottom of the water tank.

A second duct, shown in figure 2, was 7.0 centimeters wide and was formed with two 0.48-centimeter-thick hemispheres by supporting a 86.1-centimeter-outside-diameter hemisphere inside a 100.1-centimeter-inside-diameter hemisphere. A 0.16-



Top view



Side view

Figure 1. - 12.2-Centimeter hemispherical duct with 5-curie plutonium-beryllium source in water shield (experimental configuration). All dimensions are in centimeters.

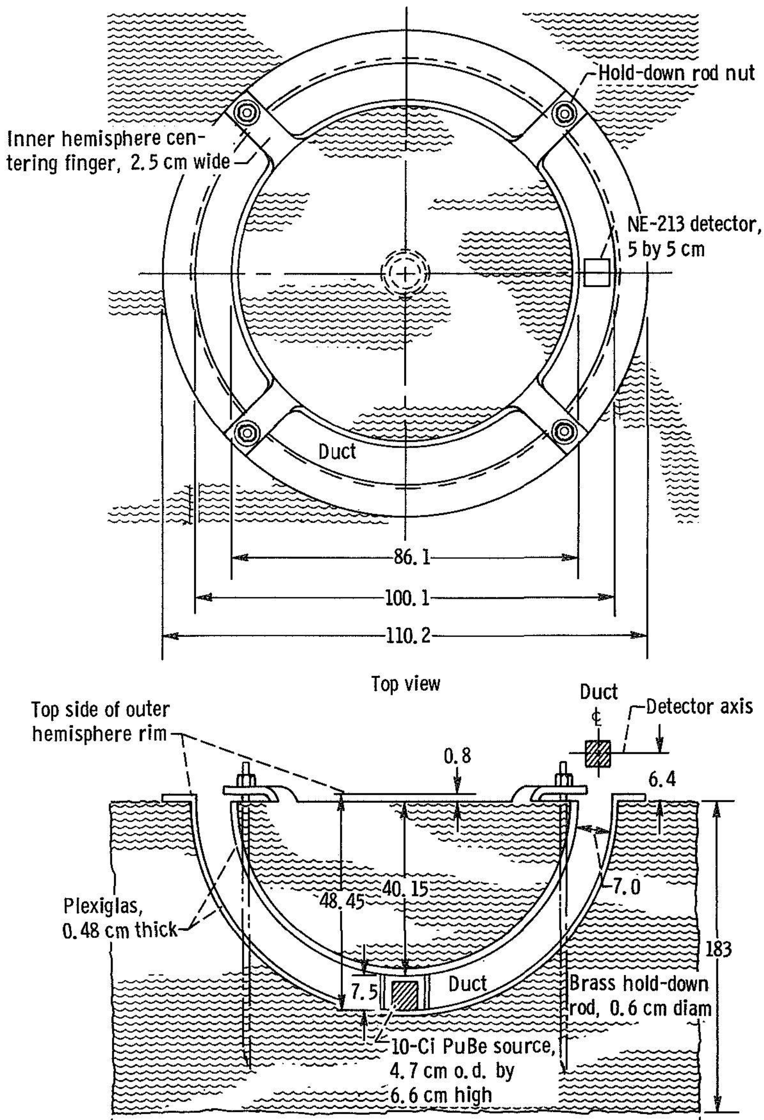


Figure 2. - 7.0-Centimeter hemispherical duct with 10-curie plutonium-beryllium source in water shield (experimental configuration). All dimensions are in centimeters.

centimeter-thick aluminum pedestal 7.5 centimeters high by 6.5 centimeters in outside diameter was used to support the inner hemisphere. Both the inner and outer hemispheres were deformed (elliptical in shape) when received from the vendor. In addition, the inner hemisphere drooped atop the pedestal when filled with water because of its thin wall and large water load. This resulted in a duct (fig. 2) which had a 7.0-centimeter width at the duct mouth and a 7.5-centimeter width at the duct bottom.

A 5-curie PuBe source (number M-682) 3.3 centimeters in outside diameter by 6.9 centimeters high was located at the bottom of the 12.2-centimeter duct. This source had a neutron yield of 1.03×10^{7} neutrons per second. A 10-curie PuBe source (number MRC-344) 4.7 centimeters in outside diameter by 6.6 centimeters high was positioned at the bottom of the 7.0-centimeter duct. The neutron yield of this source was 1.83×10^{7} neutrons per second. The intensity and spectrum of fast neutrons leaking from the duct mouth were measured with the center of the detector at 6.4 centimeters above the surface of the water. One set of flux measurements was made with the ducts empty and another set with the ducts flooded.

Spectrometer

A 5.10- by 4.65-centimeter-diameter NE-213 liquid scintillator mounted on an 8575 photomultiplier tube was used to measure neutron spectra. A modified Owen's pulse shape discrimination circuit (ref. 3) was used. The output of the pulse shape circuit and a linear output from the 10th dynode of the photomultiplier tube were amplified using commercially available White cathode followers and multimode amplifiers, and recorded in a 64 by 64 two-parameter analyzer.

The proton recoil and Compton recoil spectra were measured at three gain settings in the ratio of approximately 8 to 1 to 1/8. The photomultiplier tube was operated at 2000 volts for high- and medium-gain data, and at 1600 volts for low-gain data. The detector was calibrated at both 2000 and 1600 volts using a sodium-22 (^{22}Na) gamma source.

The FERDOR code (ref. 4) and the ORNL response functions for a 4.60- by 4.65-centimeter-diameter scintillator were used to unfold the measured proton-recoil distributions. To permit use of the ORNL response functions, the proton-recoil count rates were reduced 12 percent to account for the greater length of the NE-213 scintillator.

The uncertainty in the measured fluxes was determined from the counting statistics, the inherent uncertainty in the unfolding process, and an estimated error in the response functions used for the spectrometer. The statistical and unfolding uncertainty are included in the FERDOR method, but the response function error is more difficult to determine. A comparison of the proton-recoil distribution for 2.84-MeV neutrons measured with our spectrometer and the distribution used in FERDOR shows agreement in

shape but a disagreement of 6 percent in the leading-edge energy. In the present measurements, the neutron angular distribution is not parallel and incident on the curved surface of the scintillator as the FERDOR response functions require. Some idea of the resulting error was obtained by measuring a PuBe spectrum incident on the curved surface and then on the flat face of the scintillator. These measurements show no differences for neutron energies above 2 MeV, and differences of the order of 15 percent for neutron energies below 2 MeV. A comparison of the integrated flux measured for the PuBe source and the flux based on source strength shows agreement to within 10 percent ($E > 0.5$ MeV); this comparison requires an extrapolation of the measured flux from 0.5 to 0 MeV. Age measurements (ref. 5) reduce the uncertainty in this extrapolation. Based on the 2.84-MeV proton-recoil measurement and the PuBe source measurement, the measured duct spectra should be accurate to ±15 percent with the exception of the data around 1 to 2 MeV, which could be low by ~15 percent depending on the angular distribution of the flux.

ANALYSIS

The COHORT-II Monte Carlo shielding code was used to calculate neutron energy spectra from 0.5 to 10.8 MeV at a point detector located at the center position of the NE-213 organic scintillator. COHORT-II is a general-purpose Monte Carlo shielding code that can handle geometric boundaries describable by quadratic surfaces. The code input requires an accurate description of the source, shield geometry, and materials, and point-valued cross sections for the material elements. The code output consists of uncollided and scattered number fluxes at the detector points as a function of energy.

For the computer analysis, the 12.2-centimeter-duct geometry (fig. 3) very closely represented that of the experiment (fig. 1). The 7.0-centimeter-duct geometry (fig. 2) was approximated by a circular duct formed by two hemispheres with concentric centers (fig. 4).

The outside diameter of the inner hemisphere in figure 4 is the average of the 86.1-centimeter lateral radius and the 80.3-centimeter vertical radius, as shown in figure 2. The inside diameter of the outer hemisphere is simply 14 centimeters larger than the outside diameter of the inner hemisphere. This resulted in an inner hemisphere having an outside diameter of 83.2 centimeters and an outer hemisphere with a 97.2-centimeter inside diameter for the calculations. The physical properties of the plexiglas were taken to be those of methyl methacrylate with a density of 1.18 grams per cubic centimeter and a molecular formula of $C_5H_8O_2$. The 0.16-centimeter aluminum pedestal for the 7.0-centimeter duct was approximated as water in the calculations.

The Anderson-Bond PuBe neutron energy spectrum (ref. 6) was used as the source energy distribution for the calculations. Subsequent bare source measurements made

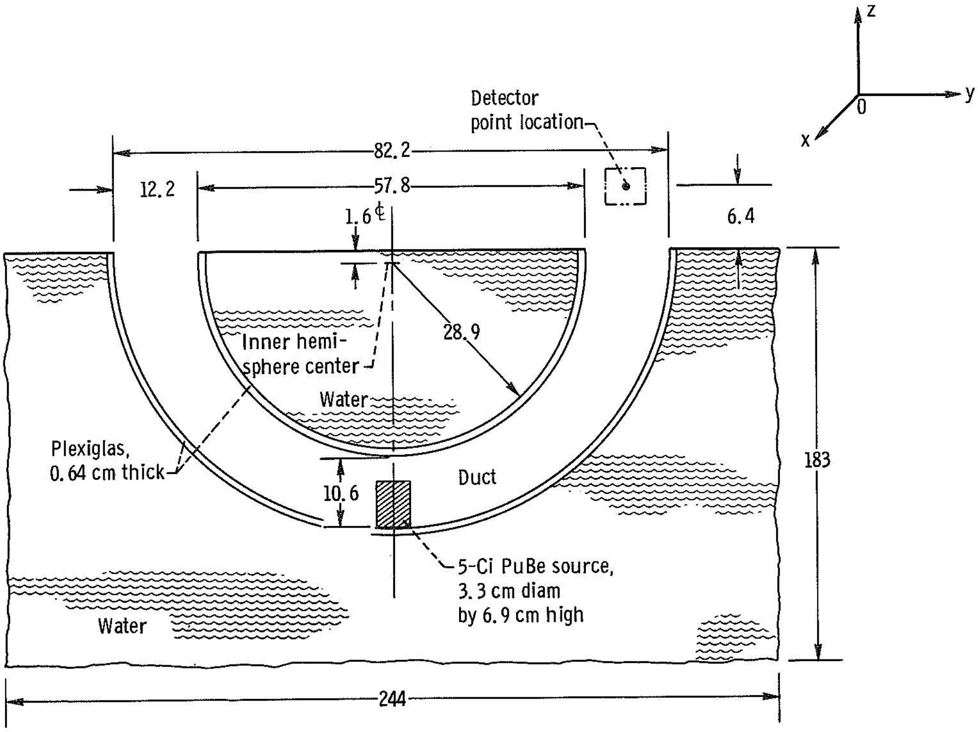


Figure 3. - 12.2-Centimeter hemispherical duct with 5-curie plutonium-beryllium source in water shield (calculational model). All dimensions are in centimeters.

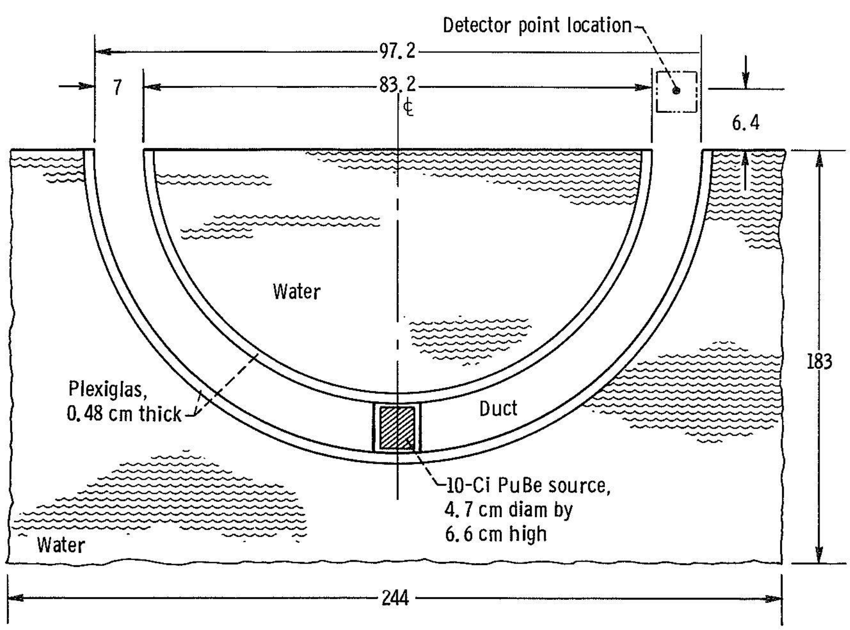


Figure 4. - 7.0-Centimeter hemispherical duct with 10-curie plutonium-beryllium source in water shield (calculational model).

with the NE-213 system were essentially the same as the Anderson-Bond spectrum. Over the energy range from 0.5 to 10.8 MeV, the source spectrum was broken up into 40 energy intervals of 0.25 MeV each and one interval of 0.30 MeV. The curve was then normalized to a source of 1 neutron per second so that

$$\int_{0.5}^{10.8} N(E)dE \cong \sum_{i=1}^{41} N_i(E)\Delta E_i = 1.0 \text{ neutron/sec}$$

where N(E) is the differential number spectrum representing the PuBe source distribution. The normalized distribution is shown in figure 5. Some energy biasing was used

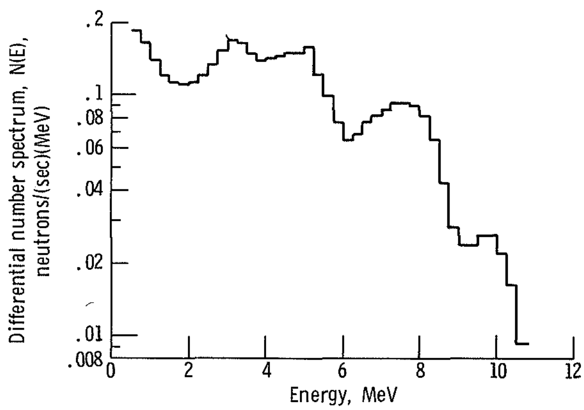


Figure 5. - Anderson-Bond 5-curie PuBe neutron source spectrum from 0.5 to 10.8 MeV.

to enhance the selection of high-energy neutrons for the flooded-duct calculations. Neutrons were spatially distributed uniformly over the volume of the PuBe sources used in both duct calculations. The material in the source region was taken as void since the Anderson-Bond spectrum is a measured one that already has the collisions with the source material taken into account.

Several biasing schemes were used in an attempt to reduce the variance in the calculated fluxes at deep penetrations. Source particle biasing consisted of a combination of energy and angular biasing of the source neutrons. Energy biasing was done by selecting neutron energies from a biased distribution. Angular biasing was done independently in both polar and azimuthal angular directions. In the polar angular bias, 90 percent of the neutrons were emitted in the upper solid-angle hemisphere and 10 percent were emitted in the lower hemisphere. Polar angles were measured from the positive z-axis. Since the point detectors were located along the y-axis, azimuthal angle fractions of

5, 75, and 20 percent were emitted in the angular intervals of 0° to 45°, 45° to 135°, and 135° to 360°, respectively. In the flooded-duct calculations, all three source particle biasing methods were used; while, for the empty duct, only azimuthal angular biasing was used.

The exponential transform biasing method was used in the transport of particles through the shield. In this technique, the actual total cross section Σ is replaced by a fictitious cross section according to the equation $\Sigma^* = \Sigma(1 - k)$, where k is a biasing parameter to be varied by the user. A biasing parameter of $k = 0.3$ was used to stretch the mean flight path of neutrons by about 43 percent in all directions. The exponential transform was applied in all the material regions for the flooded duct, but only in the upper water hemisphere for the empty-duct calculations.

The differential number fluxes were calculated at the duct mouth for each duct in the empty- and flooded-duct conditions. A source of 20 000 neutron histories was analyzed in each computer run. Typical running time on the IBM 7094 for a 20 000-history analysis was 25 minutes for a single detector point.

RESULTS AND DISCUSSION

The calculated and measured differential number fluxes for the detector located at the center of the 12.2-centimeter duct are shown in figure 6. The empty-duct fluxes are in excellent agreement. The 1-sigma error bars for the calculated spectrum range from 6 to 17 percent with a typical error of 10 percent. The calculated and measured integrated fluxes for neutrons of energy from 1.0 to 10.8 MeV shown in table I demonstrate the agreement of these curves. The calculated spectrum for the flooded duct, however, shows only fair agreement with the measured spectrum. Even though the integrated fluxes in table I agree to within 3 percent, the statistics on the individual energy bins show errors as high as 53 percent. The 50-centimeter distance from the source to detector represents about 10 mean free paths for a neutron at the average source energy of 4.0 MeV. The large fluctuation in statistics of individual energy bins indicates inadequate sampling at this penetration. The effect of the 12.2-centimeter duct can be observed by comparing the empty-duct spectra with the flooded-duct spectra. The empty-duct spectra are softer than the spectra for the flooded duct, as evidenced by the large number of low-energy neutrons that are streaming up the duct. The ratio of the integrated fluxes, shown in table I, indicates that the duct is transmitting 9.6 to 10.3 (calculated against measured, respectively) times more neutrons when empty than when flooded, when no streaming exists. The streaming of low-energy neutrons adds significantly to the total flux emerging from the duct mouth.

The calculated and measured spectra for the detector located at the center of the

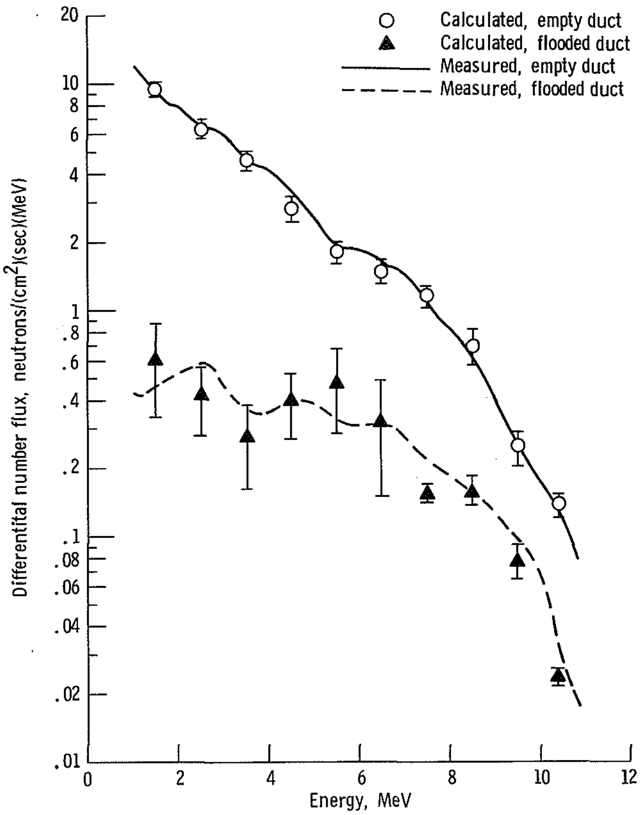


Figure 6. - Differential number flux for 12.2-centimeter hemispherical duct in water shield.

TABLE I. - COMPARISON OF INTEGRATED FLUXES FROM 1.0 TO 10.8 MeV AT DUCT MOUTH FOR 7.0- AND 12.2-CENTIMETER DUCTS

Duct		Integrated flux, neutrons/(cm^2)(sec)	
Size, cm	Contents	Measured	Calculated[a]
12.2	Empty	29.8±4.5	28.6±1.09
	Flooded	2.90±0.44	2.98±0.60
	Ratio of empty to flooded	10.3	9.6
7.0	Empty	11.25±1.69	8.39±0.27
	Flooded	1.32±0.20	1.04±0.12
	Ratio of empty to flooded	8.56	8.07

[a]Calculated errors do not include the uncertainty (estimated to be about 7 percent) in the PuBe source strength above 1.0 MeV.

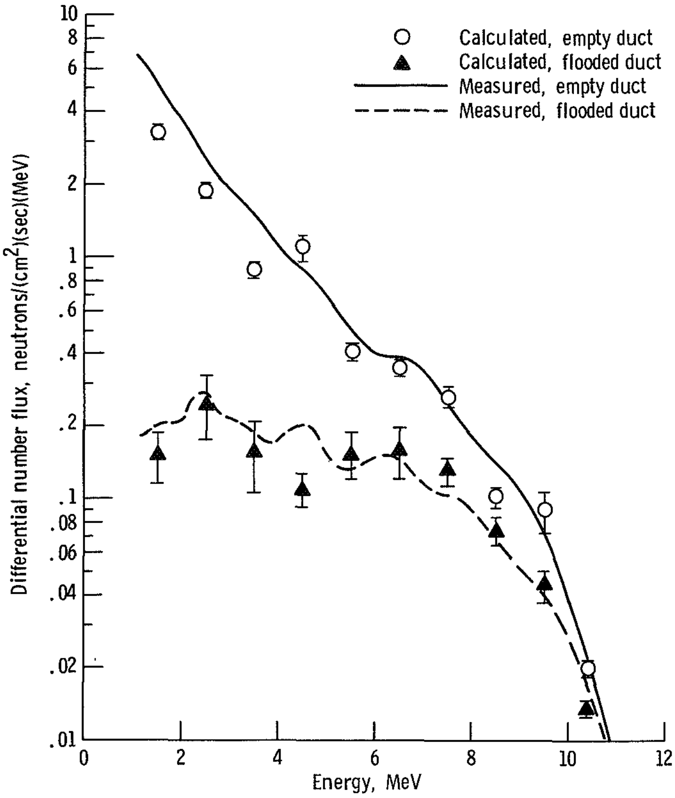
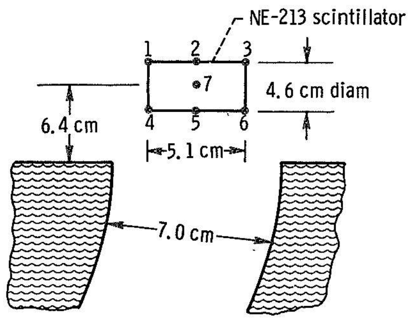


Figure 7. - Differential number flux for 7.0-centimeter hemispherical duct in water shield.

7.0-centimeter duct are shown in figure 7. This duct was the more difficult to calculate because of the smaller duct width and a larger duct center radius of 45.1 centimeters. The agreement of the curves, in general, is good. The 1-sigma error bars in the calculated spectrum at the mouth of the empty duct show a typical error of 10 percent for the individual energy bins. The integrated fluxes in table I agree to within about 25 percent with experiment. The calculated and measured spectra for the flooded duct show a similar increase in statistical error as a result of the deeper water penetration.

In a preliminary analysis, the gradient in the vicinity of the scintillator located at the mouth of the 7.0-centimeter empty duct was investigated. Calculations of flux spectra were made at several detector locations along the perimeter of the scintillator (detection points 1 to 6) and at the center position (detection point 7), as shown in figure 8. A source of 20 000 neutron histories was analyzed; the integrated fluxes at the seven detector points are shown in the table accompanying figure 8. The shape of the energy spectrum at each detector was essentially the same as the empty-duct histogram shown in figure 7, except for detector 6 which showed a significantly softer spectrum. The integrated fluxes vary from 6.43 to 12.42 neutrons per square centimeter per second (detection points 1 and 6, respectively) diagonally across the scintillator,



Monte Carlo detector numbers	Integrated fluxes, neutrons/(cm^2)(sec)
1	6.43±0.49
2	7.15±0.56
3	8.85±0.61
4	7.00±0.61
5	9.43±0.74
6	12.42±0.84
7	7.43±0.57

Figure 8. - Location of NE-213 scintillator, and integrated fluxes at seven detector points.

with a flux of 7.43 neutrons per square centimeter per second calculated at the center. These calculations suggest that a flux gradient of a factor of about 2 could exist across the scintillator for this duct measurement. Since it was not clear from these results where the detector point should best be located, the fluxes in this report were calculated with the detector located at the center position of the scintillator.

CONCLUDING REMARKS

Experimental and analytical studies were made of the fast-neutron fluxes streaming from the mouth of two hemispherical shell ducts in a water shield. Neutron flux calculations were made using the COHORT-II Monte Carlo computer code to test the ability of the program to accurately determine the fluxes. The calculated spectra and integrated fluxes were compared with experimental measurements. In general, the agreement of calculated and measured values was good.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 22, 1969,
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